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PERFORMANCE OF A SHORT MODULAR TURBOJET COMBUSTOR SEGMENT USING ASTM-A1 FUEL

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16. Abstract

A 27-inch (68.6-cm) long rectangular combustor segment consisting of an array of 48 combustor modules was tested to determine its performance. Each module mixed and swirled fuel with air and stabilized combustion. Test conditions were inlet temperatures of 600° and 1150° F (589 and 894 K), a pressure of 3 atmospheres, and reference velocities to 160 ft/sec (48.8 m/sec). Results were combustion efficiencies of 100 percent, a pressure loss of 5.4 percent for an inlet Mach number of 0.25, a heat release rate of 11.86×10^{6} Btu/(hr)(ft^{3})(atm) for a temperature ratio of 2.5, and pattern factor spans of 0.30 to 0.37 and 0.22 to 0.28 with 600° and 1150° F (589 and 894 K) inlet air temperatures, respectively. Altitude blowout and relight data, as well as a comparison of results with a longer combustor, are also included.

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SEGMENT USING ASTM-A1 FUEL

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SUMMARY

The performance of a rectangular turbojet combustor segment consisting of an array of 48 combustor modules was evaluated. The combustor was 12 inches (30.5 cm) high, 30 inches (76.2 cm) wide, and 27 inches (68.6 cm) long from the diffuser inlet to the combustor exit plane.

Test conditions were inlet air temperatures of 600° to 1150° F (589 and 894 K), a combustor pressure of 3 atmospheres, reference velocities to 160 feet per second (48.8 m/sec), and average combustor exit temperatures to 2400° F (1589 K). Good performance was demonstrated over the entire span of test conditions. Combustion efficiencies were near 100 percent for fuel-air ratios greater than 0.015. A volumetric heat release rate of 11.86×10^{6} Btu/(hr)(ft^3)(atm) was obtained for a combustor exit-to-inlet temperature ratio of 2.5 and a reference velocity of 150 feet per second (45.7 m/sec). The total pressure loss was 5.4 percent at a diffuser inlet Mach number of 0.25 and a combustor exit-to-inlet temperature ratio of 2.5. Combustor exit temperature distribution improved with increasing inlet air temperature. With 600° F (589 K) inlet air, exit temperature pattern factors were between 0.30 and 0.37. Pattern factors reduced to 0.22 to 0.28 with 1150° F (894 K) inlet air. No combustor durability problems were encountered. Maximum metal temperatures on the modules were below 1470° F (1072 K). The combustor could be relit at ambient pressure conditions and inlet air temperatures as low as 80° F (300 K) when a fuel nozzle was inserted in the array in place of one of the combustor modules.

In comparison with other modular-type combustors which have been previously investigated, the combustor reported herein produced 100-percent combustion efficiency with a shorter combustor length, lower pressure drop, and improved durability. However, the outlet temperature profiles were somewhat less uniform than for some earlier modular combustors.

INTRODUCTION

The Lewis Research Center is engaged in research directed toward development of combustors for advanced turbojet engine applications (ref. 1). Combustors consisting of arrays of combustor modules constitute one phase of this research. Combustor arrays have demonstrated promising results with gaseous fuels (refs. 2 and 3), with vaporized liquid fuels (ref. 4), and with liquid fuels (refs. 5, 6, and 7). The objectives of the present investigation were to

(1) Reduce the combustor length of the reference 7 combustor by 6 inches (15.24 cm), thereby increasing the volumetric heat release rate while maintaining high combustion efficiency and acceptable combustor exit temperature distributions

(2) Reduce the pressure loss of the reference 7 combustor by a diffuser modification

(3) Improve relight characteristics of liquid-fuel modular arrays at ambient inlet air temperatures and pressures

Combustor modules require three components for liquid-fuel applications: an inlet section which serves as a carburetor, a swirler, and a flame-stabilizer. In operation, combustion air enters the carburetor and mixes with fuel. The mixture passes through a swirler and ignites in the wake of the flame stabilizer. Secondary combustion air flows axially past the modules, recirculates in their wakes, and completes the combustion reaction. Module walls do not extend into the burning zone. Mixing of diluent air and combustion products occurs due to recirculation and eddy diffusion.

The modular combustor arrays investigated to date have shown the following advantages:

(1) Improved durability and simplicity of design since diluent air entry ports, frequently the source of liner failure, were not required

(2) An elimination of nozzle fouling problems, common at high combustor operating temperatures and pressures, by the use of a low-pressure fuel system with large fuel passages within the combustor and control orifices located outside the combustion zone

(3) An adjustable combustor exit temperature profile, achieved by varying the amounts of fuel supplied to each combustor module or module row

(4) A reduction of smoke formation by premixing of fuel and air in the modules

Previous investigations of liquid-fuel modular combustor arrays have been directed toward reductions of combustor length and module size. The combustor modules of reference 5 were 2.9 inches (7.37 cm) in diameter and 8 inches (20.32 cm) long. Due to the large module size, a combustor length from compressor exit to turbine inlet of 39 inches (99.1 cm) was required and the maximum number of modules in the array was restricted to 22. The combustor modules of reference 6 were 2.0 inches (5.08 cm) in diameter and 3.5 inches (8.90 cm) long. The reduced module size permitted a 48 module array and reduced the combustor length to 33 inches (83.82 cm). Since it had been shown that size reductions improved combustor performance, module lengths were reduced further in reference 7 to 1.56 inches (3.96 cm) and operated at a combustor length of 33 inches (83.82 cm). The conical "cans" which had been used in earlier modular combustors were replaced by flat-plate flameholders in order to improve durability. The present investigation utilized the combustor modules of reference 7 with the combustor length reduced to 27 inches (68.58 cm).

APPARATUS

Facility

The test section was housed in the closed-duct test facility shown in figure 1. The facility was connected to the laboratory air supply and exhaust systems. Remote-control valves upstream and downstream of the test section regulated airflows and combustor pressure. An indirect fired heat exchanger supplied heated air to 600° F (589 K). Higher inlet air temperatures were obtained by using a direct fired (vitiating) preheater. Baffles downstream of the vitiating preheater, a bellmouth, and a constant-area section produced uniform temperature and airflow profiles at the diffuser inlet.

Test Section

The test section (fig. 2) simulated a 90° segment of a full annulus turbojet engine combustor with a 57-inch (1.45-m) outer diameter. The test section was rectangular in cross section, 12 inches (30.5 cm) high and 30 inches (76.2 cm) wide. The diffuser had an included angle of 33°. Two diffuser inserts were installed in the upstream end of the diffuser, as shown in figure 2. The inserts were symmetrical, had an included angle of 10°, and extended 6.5 inches (16.51 cm) into the diffuser. The diffuser also contained the combustor module array which was positioned so that the module trailing edges were approximately 2 inches (5 cm) upstream of the diffuser exit. An exit ramp completed the test section. The length from the diffuser inlet to the combustor exit plane was 27 inches (68.6 cm). A film-cooled liner, extending from the diffuser exit to the combustor exit plane, protected the housings.

Combustor Module Design

The combustor module design is shown in figure 3. Each module contained three components: an inlet carburetor where fuel and air mixed, a swirler through which the mixture passed prior to combustion, and a flat plate which served as a flame stabilizer. This combustor module design was previously described in reference 7. Fuel was supplied to each combustor module through a 0.19-inch (0.48-cm) inside diameter tube. The tube injected fuel tangentially into the carburetor. A control orifice was installed in the fuel tube and located outside the combustor external to the housing.

Combustor Module Array

Forty-eight combustor modules comprised the array. The combustor modules were positioned in four horizontal rows of 12 each, as is shown in figure 4(a) view looking downstream and figure 4(b) view looking upstream. The corners of each flat-plate flame stabilizer intersected the midpoints of adjacent flame stabilizers, as shown in figure 4(c), thereby providing a continuous path across the array for flame propagation. A 0.63-inch (1.60-cm) wide metal strip was welded across both the top and bottom of the array for further flame propagation and to increase blockage along the inner and outer periphery of the array. The strips were attached to the flat plates and reduced the open flow area along the diffuser walls at the trailing edge of the array to 0.13-inch (0.32-cm) wide slots.

Combustor Models

Two combustor models were investigated with different amounts of fuel supplied to each horizontal row of combustor modules. The combustor models were identical in all other respects. For combustor model 1, the fuel orifice diameters from top to bottom were 0.043, 0.036, 0.036, and 0.043 inch (0.11, 0.09, 0.09, and 0.11 cm). For combustor model 2, the fuel orifice diameters from top to bottom were 0.040, 0.036, 0.036, and 0.049 inch (0.10, 0.09, 0.09, and 0.12 cm).

Ignition

A capacitor discharge-type ignition system which supplied a maximum energy of 20 joules to the spark ignitor lit the combustors. The ignitor was positioned approximately 1 inch (2.54 cm) downstream of the array's trailing edge.

Instrumentation

Details of instrumentation are contained in appendix A. Fixed temperature and pressure probes were located at the diffuser inlet. A traversing probe measured temperatures and pressures at the combustor exit plane. A periscope, mounted downstream of the combustor, provided a view of burning during test runs.

TEST CONDITIONS

Test were conducted over a range of fuel-air ratios at the combustor conditions given in table I. All testing was done at a nominal combustor inlet pressure of 3 atmospheres. At each reference velocity, fuel-air ratios were increased until a local combustor exit temperature exceeded 2700° F (1756 K). Additional blowout and relight tests were conducted at reduced combustor inlet temperatures and pressures.

A jet-type fuel conforming to ASTM-A1 specifications was used for all tests. This fuel had an average hydrogen-carbon ratio of 0.161 and a lower heating value of 18 600 Btu per pound (43 300 J/g).

RESULTS AND DISCUSSION

Combustor Evaluation

Combustor models were evaluated by determining combustion efficiency, pressure loss, and combustor exit temperature distribution at the test conditions given in table I. Test results are summarized in table II for combustor model 1 and in table III for combustor model 2.

Combustor exit temperature distribution was the main criterion by which performance was judged since combustion efficiencies of both models proved to be near 100 percent for the fuel-air ratios of prime interest (greater than 0.02) and the pressure loss for both models was identical. The model 2 combustor produced the most uniform combustor exit temperature distributions and was the one most extensively studied.

In general, both combustor models performed well over the span of test conditions investigated. Flames were short and blue and did not extend through the combustor exit plane at any of the test conditions.

Combustion Efficiency

Combustion efficiency was defined as the ratio of mass-weighted average temperature rise to theoretical temperature rise. The mass-weighted average exit temperature used for efficiency calculations was based on the total number of readings taken at the combustor exit plane (in excess of 385). Oxygen depletion resulting from vitiation of the combustion air at the 1150° F (894 K) inlet air temperature condition was taken into account in combustion efficiency calculations.

Combustion efficiencies of combustor models 1 and 2 with 600° F (589 K) inlet air are presented in figures 5(a) and (b), respectively. Both models produced the same combustion efficiency values. Combustion efficiency improved with increasing fuel-air ratio and decreasing reference velocity. At fuel-air ratios greater than 0.015, combustion efficiencies were near 100 percent. Combustion efficiency results are presented in figure 5(c) for the model 2 combustor with 1150° F (894 K) inlet air. At the higher inlet air temperature, combustion efficiency was not affected by reference velocity or fuel-air ratios.

Volumetric Heat Release Rate

Volumetric heat release rate was defined by the expression

$$\text{Heat release rate} = \frac{\text{Btu/hr}}{V_c P_c}$$

where V_c is the combustion volume measured from the fuel entry plane to the combustor exit plane in cubic feet and P_c is the combustor pressure in atmospheres. Maximum values of heat release rate were obtained with the model 2 combustor and were 7.84×10^6 and 11.86×10^6 Btu/(hr)(ft^3)(atm) for reference velocities of 100 and 150 feet per second (30.5 and 45.7 m/sec), respectively, with 600 F (589 K) inlet air. The combustor exit-to-inlet temperature ratio for both cases was 2.5.

Pressure Loss

Combustor total-pressure loss $\Delta P/P$ includes the diffuser pressure loss and is defined by the following expression:

$$\Delta P/P = \frac{\text{Average diffuser inlet total pressure} - \text{Average combustor exit total pressure}}{\text{Average diffuser inlet total pressure}}$$

Figure 6 shows the variation of pressure loss with diffuser inlet Mach number for combustor models 1 and 2. Since both models were geometrically identical and differed only in fuel distribution, their pressure loss was identical. At a diffuser inlet Mach number of 0.25 and a combustor exit-to-inlet temperature ratio of 2.5, their pressure loss was 5.4 percent.

Combustor Exit Temperature Distribution

Average radial temperature profiles. - Average radial temperature profiles for both combustor models are shown in figures 7(a) and (b). At each radial position, combustor exit mass-weighted temperatures were averaged circumferentially. The difference between these values and the mass-weighted average temperature are plotted against radial position. Radial position is expressed as percentage of combustor exit height. The ideal radial profile shown on these plots is representative of the requirements of current supersonic turbojet engines. Model 1 radial profiles had cold zones along the inner annulus and hot zones at the 79 percent combustor exit height. Tailoring the fuel flow to the modules in model 2 improved the radial profile. Average radial profiles matched the ideal profile more closely at the higher combustor inlet air temperature.

Average circumferential temperature profiles. - Combustor exit non-mass-weighted temperatures, averaged along a radius and plotted against circumferential position for combustor model 2 are shown in figures 8(a) and (b) for two inlet air temperatures. Profiles again improved as the combustor inlet air temperature was increased. A maximum positive deviation of 227° F (126 K) occurred between the average exit temperature and the maximum average at any circumferential location with 600° F (589 K) inlet air. This span was reduced to 147° F (82 K) when 1150° F (894 K) inlet air was supplied even though the average temperature was increased from 2127° to 2434° F (1437 to 1605 K).

Temperature distribution parameters. - The temperature distribution parameters δ_{stator}, δ_{rotor}, and $\overline{\delta}$ were established to describe combustor exit temperature distributions.

$$\delta_{stator} = \frac{(T_{r,local} - T_{r,design})_{max}}{\Delta T}$$

where $(T_{r,local} - T_{r,design})_{max}$ is the largest temperature differential between the highest local temperature at any radius $T_{r,local}$ and the design temperature for that radius, and where ΔT is the average temperature rise across the combustor. The design temperature $T_{r,design}$ was obtained from a design radial temperature profile which is typical of profiles encountered in advanced supersonic engines.

$$\delta_{rotor} = \frac{(T_{r,av} - T_{r,design})_{max}}{\Delta T}$$

where $(T_{r,av} - T_{r,design})_{max}$ is the largest temperature differential between the average circumferential temperature on any radius $T_{r,av}$ and the design temperature for that radius.

Another temperature distribution parameter in common usage in the aircraft industry was also employed. This parameter is the pattern factor and is defined by the expression

$$\text{Pattern factor} = \bar{\delta} = \frac{T_{max} - T_{av}}{\Delta T}$$

where T_{max} is the highest local combustor exit temperature, T_{av} is the average combustor exit temperature, and ΔT is the combustor temperature rise. For nearly all applications, lower temperature distribution parameters are preferred.

For calculations of temperature distribution parameters, non-weighted temperatures were used. Approximately 10 percent of the temperature readings at each combustor sidewall were disregarded to eliminate the sidewall effects which are always present in sector tests.

Calculated values of δ_{stator}, δ_{rotor}, and $\bar{\delta}$ are given in table II for combustor model 1 and in table III for combustor model 2. The best temperature distribution parameters were obtained with the model 2 combustor. For fuel-air ratios greater than 0.015 and with a 600° F (589 K) inlet air temperature, δ_{stator} values varied between 0.27 and 0.32, δ_{rotor} varied between 0.06 and 0.10, and $\bar{\delta}$ varied between 0.30 and

and 0.37. These values were obtained for a reference velocity span of 80 to 150 feet per second (24.4 to 45.7 m/sec). When the inlet air temperature was increased to 1150° F (894 K), the distribution parameters improved to values of δ_{stator} from 0.19 to 0.23, δ_{rotor} from 0.09 to 0.11, and $\bar{\delta}$ from 0.22 to 0.28. Combustor model 1 temperature distribution parameters were slightly higher. These results indicate the effectiveness of improving the temperature distribution by redistribution of fuel to the module rows. No attempts beyond fuel flow adjustments to module rows were made to improve either radial or circumferential temperature profiles or temperature distribution parameters.

Altitude Blowout and Relight

Altitude blowout and relight tests were made for combustor model 2. Blowout points were obtained by setting the combustor inlet air temperature and pressure and increasing airflow until blowout occurred. This procedure was repeated for combustor inlet air temperatures decreasing from 600° to 100° F (589 to 311 K) and inlet total pressures of 2.5 to 0.5 atmospheres. The fuel-air ratio for all tests was nominally 0.018. Blowout occurred when less than one-half to two-thirds of the combustor modules were lit or when additional fuel did not produce corresponding increases in combustor exit temperature. Once the combustor blowout points were determined, attempts were made to ignite the combustor as near to the blowout points as possible. Blowout and relight tests were made with vitiated air. Vitiation tends to adversely affect combustion efficiency, combustion stability, and relight. The effects of vitiation on combustion efficiency for a modular combustor array are presented in appendix B.

Results of blowout and relight tests are given in figures 9(a) and (b). They agree with results obtained with the reference 7 combustor. The combustor was stable over the entire range of temperatures and pressures investigated. However, as inlet air temperatures and pressures were decreased, the maximum reference velocity for which stable burning could be maintained also decreased. With 600° F (589 K) inlet air, combustion was stable for reference velocities greater than 200 feet per second (61 m/sec). As the inlet air temperature was decreased to 100° F (311 K) reductions of reference velocity to maximum values of 80 to 150 feet per second (24.4 to 45.7 m/sec) were required to maintain combustion over a significant portion of the array.

Relight performance was similarly affected by decreasing pressure and temperature. The combustor would not ignite with 100° F (311 K) inlet air. Increasing inlet air temperature to 200° F (367 K) permitted relight over the entire span of inlet pressures.

A simplex fuel nozzle was inserted in the array in the vicinity of the ignitor in order to ignite the combustor at ambient inlet air temperatures and pressures. The purpose of the fuel nozzle was to atomize a small amount of fuel in the vicinity of the ignitor. The nozzle replaced one of the combustor modules in the bottom row. The installation is shown in figure 10. The nozzle fuel flow was fixed at 0.0012 pound per second (0.544 g/sec) with a pressure differential across the nozzle of 190 psid (5.44 N/m^2). Fuel to the spray nozzle and to the combustor array were separately controlled. After ignition was achieved, fuel flow to the nozzle was terminated.

With the fuel nozzle, ignition was achieved with 80° F (300 K) inlet air and 1-atmosphere pressure. Relight occurred for fuel-air ratios of 0.015 and 0.02 and reference velocities of 69, 89, and 132 feet per second (21.0, 27.1, and 40.2 m/sec). Flame propagated across the array at all these conditions. Resonance or combustion instability did not occur. Ignition could not be achieved with fuel-air ratios of 0.01, and 0.0125 or when the reference velocity was increased to 150 feet per second (45.7 m/sec).

Other combustor modifications, which were not attempted but would probably also air relight, are increasing the energy to the ignitor, replacing the spark probe with a torch ignitor, preheating the fuel and/or decreasing the airflow through the combustor modules.

Durability

Extended combustor durability tests were not made. However, no module burnout problems were encountered during performance tests. Temperature-sensitive paint showed that maximum module temperatures occurred on the flame stabilizers. These temperatures were below 1470° F (1072 K) even when 1150° F (894 K) inlet air was supplied.

Comparison of Test Results With Those of Reference 7

The present study utilized the combustor module array of reference 7 and differed only in the diffuser inserts and the combustor length. For the present study, two diffuser inserts 6.5 inches (16.51 cm) long were used and the combustor length was 27 inches (68.6 cm). For the study described in reference 7, five diffuser inserts 8.5 inches (21.59 cm) long were used and the combustor length was 33 inches (83.82 cm). Both module arrays were evaluated in the same test facility under identical conditions.

Combustion efficiency. - Combustion efficiencies for both combustors are shown in figure 11. Similar results were obtained in both studies. Thus it appears that the 6-inch (15.24-cm) reduction in combustor length had no effect on combustion efficiency. For both studies, combustion efficiency decreased at low fuel-air ratios. Since the low fuel-air ratios were not of primary interest, no attempts were made to improve performance at these conditions. Reductions in combustion efficiency at low fuel-air ratios occurring with the swirl-can modular combustor array of reference 6 were minimized by reducing the airflow through the carburetors. This was accomplished by reducing the flow area between swirler vanes by reducing vane angle. Similar swirler area flow reductions could be made for the flat-plate flame stabilizer modules.

Heat release rate. - Volumetric heat release rates for the present study were approximately one-third higher than those obtained for the longer combustor. The present study used a combustor volume of 2.057 cubic feet (0.0582 m^3). For comparative purposes, the burning volume of the reference 7 combustor was 3.165 cubic feet (0.0896 m^3).

Pressure loss. - Figure 12 compares the pressure loss of both combustors. The reference 7 value is approximately 1 percent higher at an inlet Mach number of 0.25. Since the array blockages were identical for both combustors, the difference was primarily diffuser loss. Although the two vane inserts produced less pressure loss, they did not appear to produce as uniform an airflow distribution as the reference 7 configuration. Poorer airflow distributions can be inferred by poorer radial average temperature distributions. Radial average temperature distributions for both combustors are shown in figure 13.

Combustor exit temperature distribution. - Higher temperature distribution parameters resulted with the shorter combustor: values of δ_{stator} were about 0.04 higher, values of δ_{rotor} were approximately 0.07 higher, and pattern factors $\bar{\delta}$ were about 0.05 higher. The increase in temperature distribution parameters appears to have been caused both by the shorter mixing length and by a reduction in airflow to the upper portions of the combustor array. Both local and average temperatures at the 79 and 93 percent combustor exit heights were higher for the present study, indicating that the diffuser modification may have produced an unbalanced radial airflow distribution. No attempts were made to improve the diffuser performance.

Durability. - No burnout problems were encountered with either of the combustor configurations during test runs. Maximum module temperatures were below 1470° F (1072 K).

SUMMARY OF RESULTS

A 48-module combustor-segment array was evaluated in a rectangular test section using ASTM-A1 fuel. The combustor length from the diffuser inlet to the combustor exit plane was 27 inches (68.6 cm). The modules were 1.56 inches (3.96 cm) long and consisted of a carburetor, a swirler, and a flat-plate flame stabilizer. Test conditions were an inlet pressure of 3 atmospheres, combustor inlet air temperatures of 600° and 1150° F (589 and 894 K), and reference velocities of 80 to 160 feet per second (24.4 to 48.8 m/sec).

The best combustor produced the following results:

1. Combustion efficiencies were near 100 percent for average combustor exit temperatures of 2000° F (1366 K) or greater.

2. Heat release rates to 11.86×10^6 Btu/(hr)(ft^3)(atm) were obtained for a combustor exit-to-inlet temperature ratio of 2.5 and a reference velocity of 150 feet per second (45.7 m/sec).

3. The total pressure loss (including diffuser loss) was 5.4 percent at a diffuser inlet Mach number of 0.25 and a combustor exit-to-inlet temperature ratio of 2.5.

4. Combustor exit temperature distribution improved with increasing combustor inlet air temperature and fuel-air ratio. At an inlet air temperature of 600° F (589 K), a fuel-air ratio of 0.023, and a reference velocity of 100 feet per second (30.5 m/sec), the temperature distribution parameters δ_{stator} and δ_{rotor} had values of 0.29 and 0.09, respectively. The pattern factor was 0.31. At an inlet air temperature of 1150° F (894 K), a fuel-air ratio of 0.02, and a reference velocity of 160 feet per second (48.8 m/sec), the values of these parameters were δ_{stator}, 0.21; δ_{rotor}, 0.11; and pattern factor, 0.24.

5. Altitude blowout and relight tests showed that stable combustion occurred with inlet air temperatures and pressures of 600° to 100° F (589 to 311 K) and 2.5 to 0.5 atmospheres, respectively. The combustor would relight over the entire span of pressures with inlet air temperatures of 200° F (367 K) or greater. A fuel nozzle mounted in the module array was required to ignite the combustor at ambient inlet air temperatures. With the fuel nozzle, ignition was achieved with 80° F (300 K) inlet air temperature, ambient combustor pressures, and reference velocities to 132 feet per second (40.2 m/sec).

6. A performance comparison of this study with the best performing combustor of reference 7, which was 6 inches (15.24 cm) longer and used the same module array, produced the following results:

(a) Combustion efficiencies for both studies were near 100 percent for fuel-air ratios greater than 0.015. No durability problems were encountered in either study.

(b) The present study produced volumetric heat release rates approximately one-third higher, and also produced lower pressure loss.

(c) The shorter combustor produced higher temperature distribution parameter values and less uniform combustor exit average radial temperature profiles.

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APPENDIX A

INSTRUMENTATION

Airflow rates were measured by square-edged orifices installed according to ASME specifications. Fuel flows were measured by turbine-type flowmeters which were connected to frequency-to-voltage converters.

Locations of pertinent instrumentation planes and arrangements of pressure and temperature probes are shown in figure 14. Pressures in the inlet section were measured by five rakes, each consisting of five-point total-pressure tubes, and by four wall static-pressure taps (section A-A, fig. 14). Temperatures were measured by 10 Chromel-Alumel thermocouples (section B-B, fig. 14). Combustor exit total pressures and temperatures were recorded by a movable seven-point total-pressure and seven-point total-temperature rake (section C-C, fig. 14). The exit rake is shown in figure 15. The temperature probes were platinum-13-percent-rhodium/platinum thermocouples and were the high-recovery aspirating type referred to as type 6 in reference 8. Four static-pressure taps measured static pressure at the combustor exit plane. Temperature and pressure surveys at the combustor exit were made by traversing the probe horizontally across the exit to produce approximately one reading every 0.5 inch (1.3 cm). Additional temperature and pressure instrumentation was placed in the diffuser and on the combustor liners to monitor combustor performance during test runs.

All pressures exclusive of the total pressures on the exit rake were measured and recorded by the laboratory's Digital Automatic Multiple Pressure Recorder (DAMPR). Exit probe total pressures were measured by strain-gage pressure transducers. Both transducer and DAMPR data were processed by the laboratory's Central Automatic Data Processing System (ref. 9), which also processed thermocouple and fuel flowmeter outputs.

APPENDIX B

EFFECTS OF VITIATION ON COMBUSTION EFFICIENCY

OF A MODULAR COMBUSTOR ARRAY

Tests were conducted to determine the effects of vitiation on the combustion efficiency of a modular combustor array. The combustor used for these tests was model 1 with a 6-inch (15.24-cm) long constant-area section added between the diffuser and the combustor exit ramp. The combustor length was 33 inches (83.82 cm). All testing was done at a combustor pressure of 3 atmospheres and an inlet air temperature of 600° F (589 K). Reference velocities were 75, 100, 125, and 150 feet per second (22.8, 30.5, 38.1, and 45.7 m/sec). Nominal combustor fuel-air ratios were 0.0125, 0.015, 0.0175, 0.02, and 0.0225.

Comparative tests were made for the following conditions:

(1) No vitiation.

(2) No vitiation to 300° F (422 K). Vitiating preheater used to heat the inlet air from 300° to 600° F (422 to 589 K).

(3) Vitiating preheater used to heat the air from ambient temperature to 600° F (589 K).

The vitiating preheater consisted of ten J71 single combustor cans burning white gasoline. The combustion efficiency of the vitiating preheater was 85 to 90 percent for these test conditions. Oxygen depletion by the vitiating preheater was taken into account in combustion efficiency calculations for the combustor module array.

Test results are presented in figures 16(a) to (d). In all cases, vitiation reduced combustion efficiency. Effects were particularly pronounced at lower fuel-air ratios and the higher reference velocities. At the highest fuel-air ratio investigated, 0.022, combustion efficiencies were near 100 percent for all reference velocities with and without vitiation.

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8. Glawe, George E.; Simmons, Frederick, S.; and Stickney, Truman M.: Radiation and Recovery Corrections and Time Constants of Several Chromel-Alumel Thermocouple Probes in High-Temperature, High-Velocity Gas Streams. NACA TN 3766, 1956.
9. Staff of the Lewis Laboratory; Central Automatic Data Processing System. NACA TN 4212, 1958.

TABLE I. - COMBUSTOR NOMINAL TEST CONDITIONS

[Combustor inlet total pressure, 3 atm.]

Combustor model	Combustor inlet temperature		Combustor inlet Mach number	Combustor reference Mach number	Combustor reference velocity[a]	
	^{o}F	K			ft/sec	m/sec
1	600	589	0.193	0.050	80	24.4
			.241	.063	100	30.5
			.301	.078	125	38.1
			.361	.094	150	45.7
2	600	589	0.193	0.050	80	24.4
	600	589	.241	.063	100	30.5
	600	589	.361	.094	150	45.7
	1150	894	.251	.065	130	39.6
	1150	894	.331	.086	160	48.8

[a]Reference velocity is the volumetric flow rate, based on total density at the combustor inlet, divided by the maximum cross-sectional area of the combustor housing. In this case the maximum cross-sectional area is 2.5 ft^2 (0.232 m^2).

TABLE II. - COMBUSTOR PERFORMANCE DATA FOR MODEL 1

[Nominal combustor inlet total pressure, 3 atm.]

Run	Inlet air temperature		Airflow		Diffuser inlet Mach number	Nominal reference velocity		Total combustor pressure loss, $\Delta P/P$, percent	Fuel-air ratio	Average combustor exit temperature (mass-weighted)		Combustion efficiency, percent	Maximum combustor exit temperature		Volumetric heat release rate,	Corrected for sidewall effects: Average combustor exit temperature (not mass-weighted)		Corrected for sidewall effects: Temperature distribution parameters		
	°F	K	lb/sec	kg/sec		ft/sec	m/sec			°F	K		°F	K	$\frac{\text{Btu}}{(\text{hr})(\text{ft}^3)(\text{atm})}$	°F	K	δ_{stator}	δ_{rotor}	Pattern factor, δ
1	608	593	23.84	10.81	0.202	80	24.4	3.14	------	----	----	----	----	----	--------	----	----	----	----	----
2	605	591	24.09	10.93	.207	↓	↓	3.58	0.0142	1529	1104	99.4	2021	1378	3.87×10^6	1631	1161	0.33	0.11	0.38
3	601	589	23.84	10.81	.199	↓	↓	3.62	.0166	1720	1211	103.4	2267	1514	4.40	1821	1267	.33	.14	.37
4	602	590	23.80	10.80	.200	↓	↓	3.62	.0209	1965	1347	102.3	2593	1696	5.49	2056	1397	.34	.13	.36
5	602	590	23.72	10.76	.206	↓	↓	3.70	.0231	2094	1418	102.4	2753	1704	6.11	2182	1467	.33	.15	.36
6	608	593	29.06	13.18	.253	100	30.5	4.81	------	----	----	-----	----	----	----	----	----	----	----	----
7	602	590	30.28	13.74	.260	↓	↓	5.59	.0149	1547	1114	96.4	2018	1376	5.03	1658	1176	.30	.13	.35
8	601	589	30.28	13.74	.256	↓	↓	5.76	.0169	1741	1222	101.8	2281	1522	5.76	1838	1276	.31	.15	.36
9	603	590	29.70	13.47	.256	↓	↓	5.92	.0204	1936	1331	102.1	2563	1679	6.83	2042	1389	.33	.14	.37
10	603	590	30.13	13.67	.261	↓	↓	5.91	.0222	2051	1394	102.4	2707	1759	7.64	2161	1456	.31	.13	.36
11	601	589	30.11	13.66	.252	↓	↓	5.90	.0231	2084	1413	102.0	2851	1839	7.86	2229	1493	.35	.15	.38
12	602	590	37.02	16.79	.320	125	38.1	7.01	------	----	----	-----	----	----	----	----	----	----	----	----
13	583	579	36.40	16.56	.321	↓	↓	8.57	.0151	1506	1092	92.5	2035	1386	6.32	1604	1146	.36	.12	.41
14	606	589	36.95	16.76	.324	↓	↓	9.00	.0174	1731	1217	99.3	2303	1534	7.41	1825	1269	.34	.15	.39
15	574	574	36.85	16.72	.321	↓	↓	9.05	.0198	1909	1316	102.8	2585	1691	8.39	2021	1378	.35	.14	.39
16	596	586	37.02	16.79	.329	↓	↓	9.21	.0236	2109	1427	101.8	2891	1861	10.10	2224	1491	.37	.13	.41
17	604	591	44.40	20.14	.401	150	45.7	11.97	------	----	----	-----	----	----	----	----	----	----	----	----
18	605	591	44.42	20.15	.393	↓	↓	12.98	.0147	1289	971	71.9	1856	1286	7.68	1397	1031	.50	.12	.58
19	604	591	44.03	19.97	.406	↓	↓	13.35	.0172	1609	1149	91.9	2176	1464	8.96	1711	1206	.37	.17	.42
20	577	576	44.40	20.14	.358	↓	↓	12.34	.0197	1958	1343	98.4	2635	1719	9.20	2065	1402	.34	.16	.39
21	604	591	43.66	19.80	.401	↓	↓	13.95	.0226	1995	1363	99.3	2671	1739	11.73	2135	1441	.31	.16	.39

TABLE III. - COMBUSTOR PERFORMANCE DATA FOR MODEL 2

[Nominal compressor inlet total pressure, 3 atm.]

Run	Inlet air temperature		Airflow		Diffuser inlet Mach number	Nominal reference velocity		Total combustor pressure loss, ΔP/P, percent	Fuel-air ratio	Average combustor exit temperature (mass-weighted)		Combustion efficiency, percent	Maximum combustor exit temperature		Volumetric heat release rate,	Corrected for sidewall effects: Average combustor exit temperature (not mass-weighted)		Corrected for sidewall effects: Temperature distribution parameters		
	°F	K	lb/sec	kg/sec		ft/sec	m/sec			°F	K		°F	K	$\frac{\text{Btu}}{(\text{hr})(\text{ft}^3)(\text{atm})}$	°F	K	δ_{stator}	δ_{rotor}	Pattern factor, $\bar{\delta}$
1	613	596	23.65	10.73	0.199	80	24.4	3.14	0.0099	1227	935	91.4	1581	1134	2.59	1259	994	0.42	0.11	0.50
2	601	589	24.18	10.97	.203			3.21	.0125	1428	1048	99.1	1832	1274	----	1474	1074	.32	.10	.41
3	576	575	24.42	11.08	.202			3.26	.0154	1612	1151	101.0	2110	1427	4.22	1693	1196	.32		.38
4	673	609	23.57	10.69	.201			3.49	.0167	1758	1232	102.8	2221	1483	4.36	1805	1258	.30		.35
5	584	508	23.77	10.78	.200			3.48	.0185	1792	1251	101.0	2239	1499	4.91	1851	1283	.27		.31
6	587	581	23.43	10.63	.198			3.51	.0204	1932	1329	102.8	2532	1662	5.30	2045	1391	.30	.07	.33
7	591	584	23.28	10.56	.200			3.53	.0218	2008	1371	102.3	2598	1698	5.63	2096	1419	.30	.06	.33
8	595	586	24.18	10.97	.199			3.53	.0231	2088	1415	102.3	2723	1768	6.23	2183	1468	.31	.08	.34
9	603	590	29.28	13.28	.258	100	30.5	5.13	.0101	1109	871	73.5	1475	1074	3.32	1148	893	.51	.11	.60
10	606	592	29.47	13.37	.256			5.38	.0125	1336	996	87.4	1714	1207	4.14	1387	1025	.34	.10	.42
11	593	585	29.64	13.44	.254			5.41	.0147	1517	1098	95.2	1913	1318	4.92	1569	1127	.30	.09	.35
12	593	585	29.91	13.57	.251			5.30	.0181	1763	1233	100.4	2211	1484	5.91	1818	1265	.28	.09	.32
13	593	585	29.73	13.49	.252			5.42	.0203	1905	1314	101.3	2466	1624	6.83	2018	1375	.27	.10	.31
14	592	584	29.71	13.48	.254			5.53	.0227	2021	1374	101.1	2603	1704	7.84	2127	1438	.29	.09	.31
15	602	590	43.14	19.57	.390	150	45.7	12.14	.0148	1274	963	68.6	1709	1204	7.53	1337	998	.42	.09	.51
16	594	585	43.38	19.68	.393			12.60	.0175	1613	1151	89.6	2126	1436	9.06	1713	1207	.29	.08	.37
17	598	587	43.15	19.57	.394			13.34	.0199	1854	1285	98.2	2400	1588	10.21	1983	1357	.26	.07	.30
18	602	590	43.06	19.53	.394			13.41	.0229	2043	1392	100.5	2678	1741	11.86	2187	1470	.29	.07	.32
19	1174	907	23.18	10.51	.254	130	39.6	5.12	.0106	1816	1264	100.2	2060	1399	2.67	1864	1291	.20	.09	.29
20	1178	910	23.66	10.73	.251			5.09	.0133	1980	1355	100.8	2256	1508	3.37	2062	1401	.19	.09	.22
21	1173	907	23.87	10.83	.254			5.21	.0164	2150	1450	101.2	2516	1653	4.42	2237	1495	.19	.09	.24
22	1180	911	23.72	10.76	.252			5.20	.0177	2293	1529	100.4	2684	1746	4.74	2374	1574	.21	.10	.26
23	1204	924	29.69	13.47	.341	160	48.8	8.13	.0102	1818	1264	101.4	1968	1346	3.51	1879	1296	.23	.11	.28
24	1187	915	29.57	13.41	.338			8.02	.0131	1971	1349	100.8	2280	1520	4.51	2048	1392	.23	.09	.27
25	1188	915	29.32	13.30	.334			8.04	.0159	2136	1439	102.1	2489	1638	5.38	2229	1493	.21	.09	.25
26	1187	915	29.65	13.45	.328			8.20	.0190	2298	1528	100.6	2632	1716	6.56	2387	1579	.22	.10	.24
27	1184	914	29.70	13.47	.331			8.19	.0199	2357	1563	101.2	2694	1750	6.88	2434	1605	.21	.11	.24

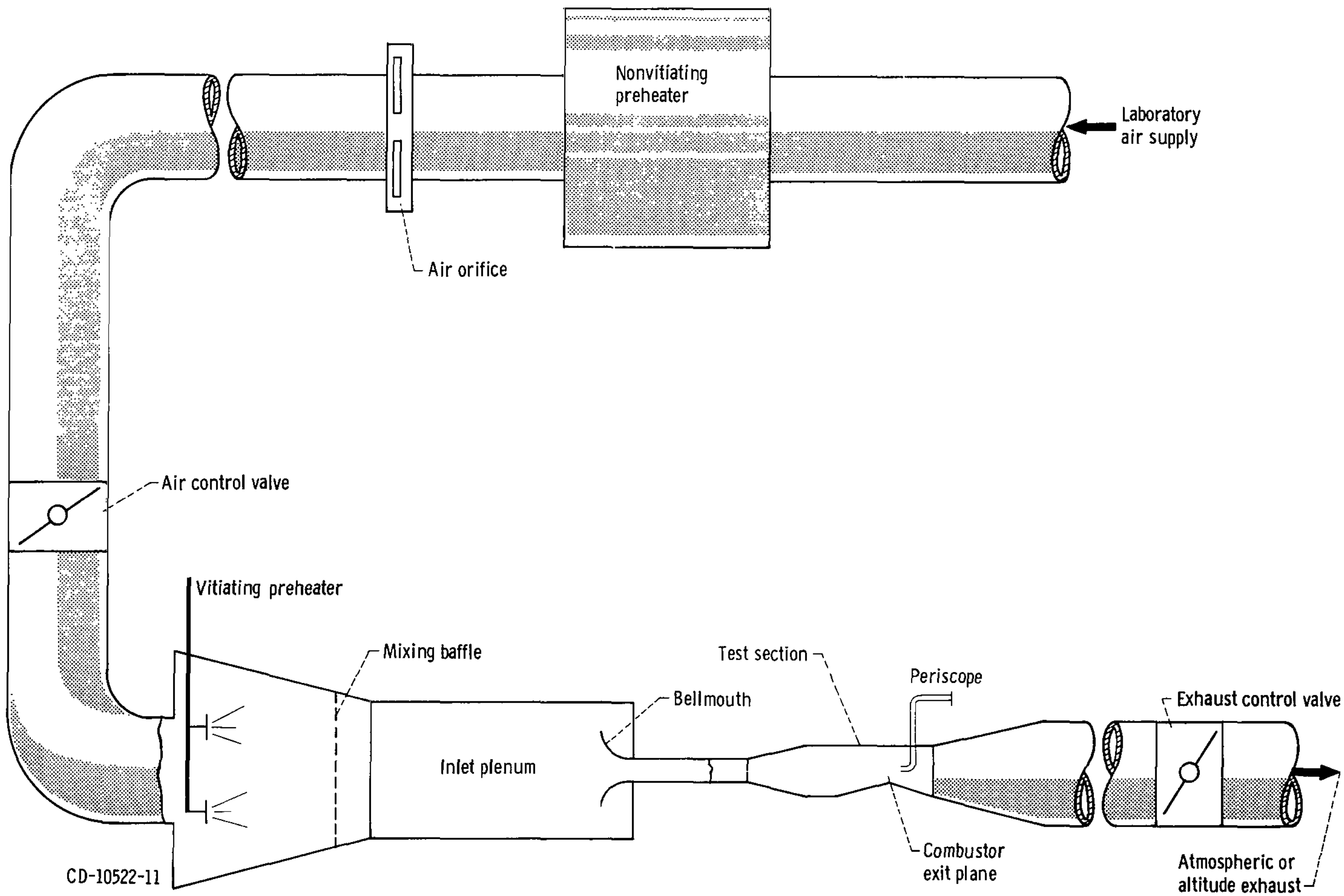


Figure 1. - Test facility and auxiliary equipment.

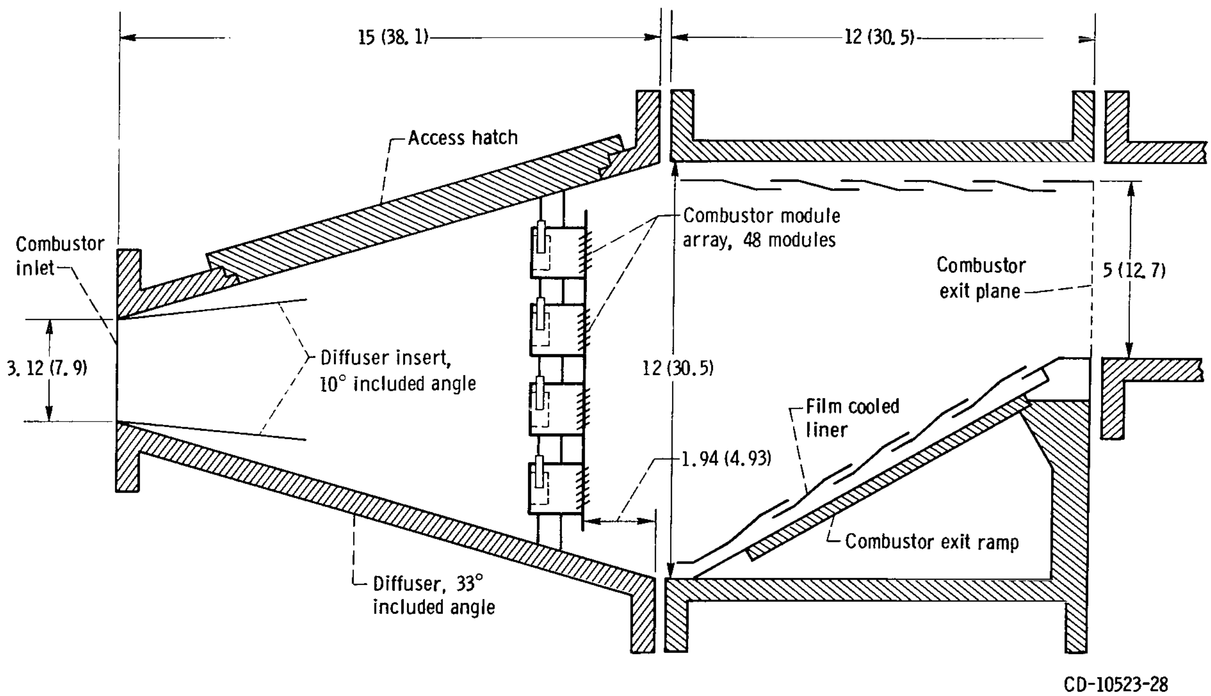


Figure 2. - Combustor installation in test section. (Dimensions are in inches (cm).)

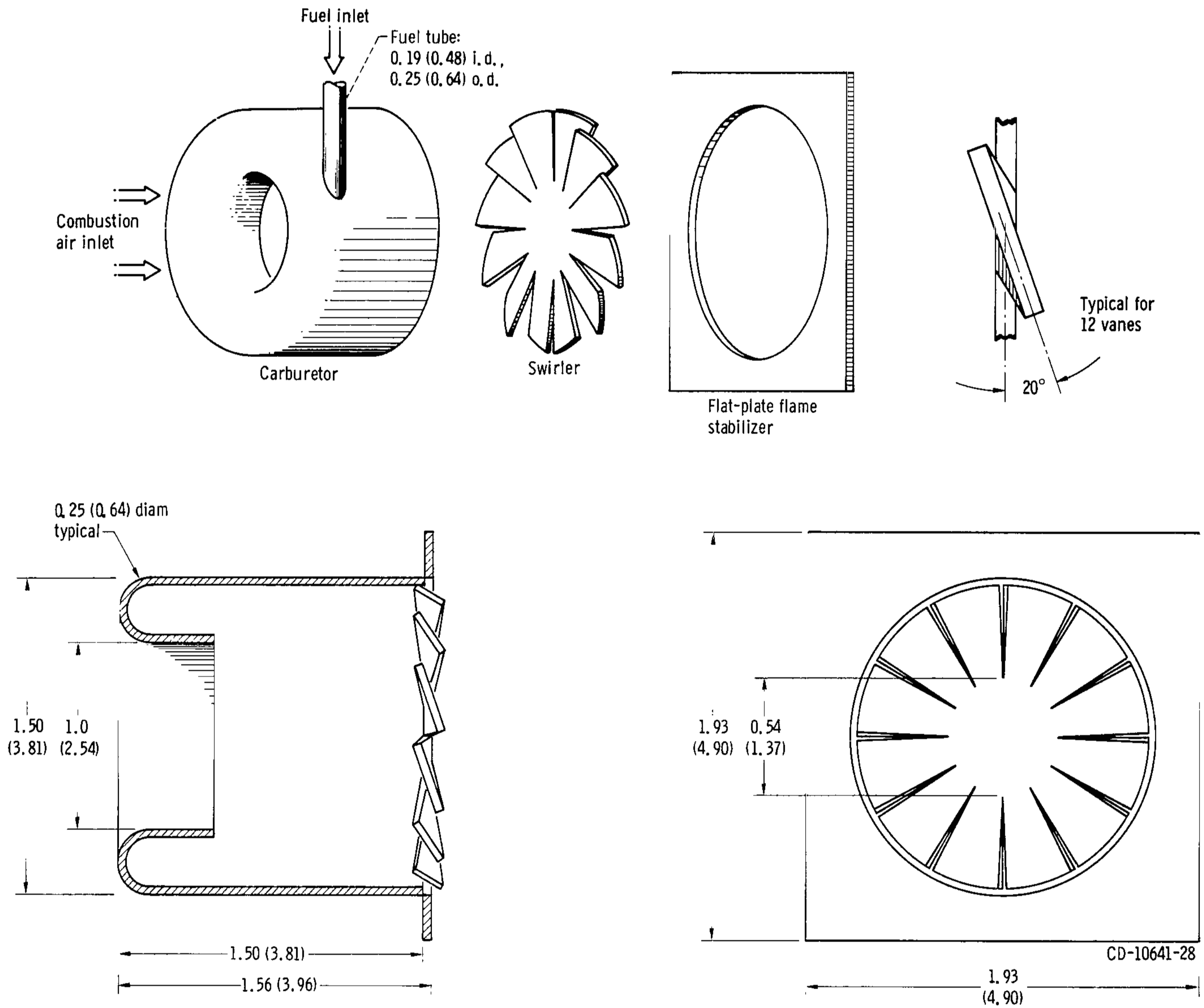
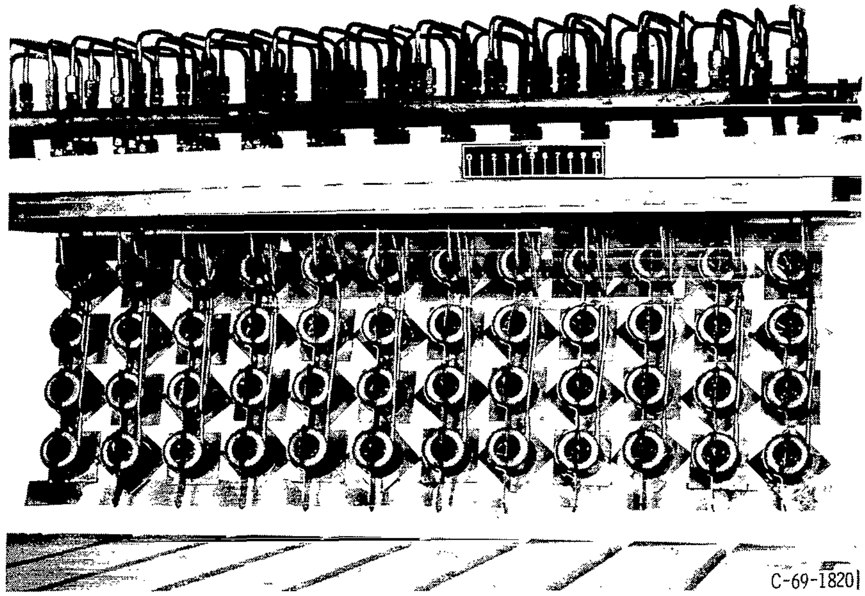
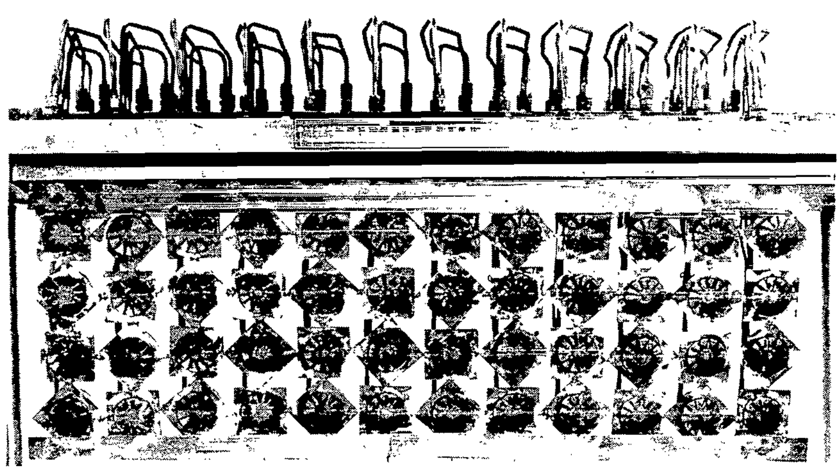


Figure 3. - Combustor module details. (Dimensions are in inches (cm).)



(a) View looking downstream.



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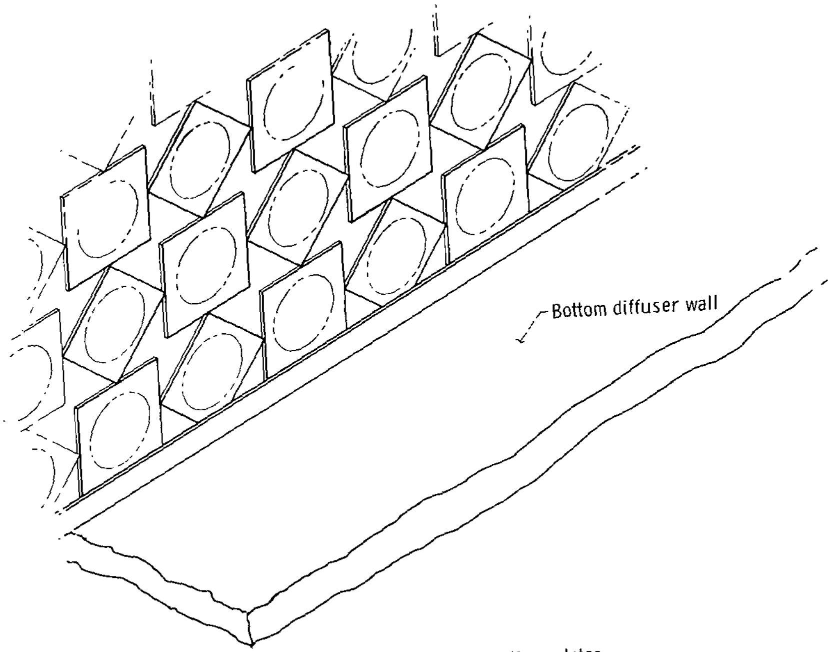
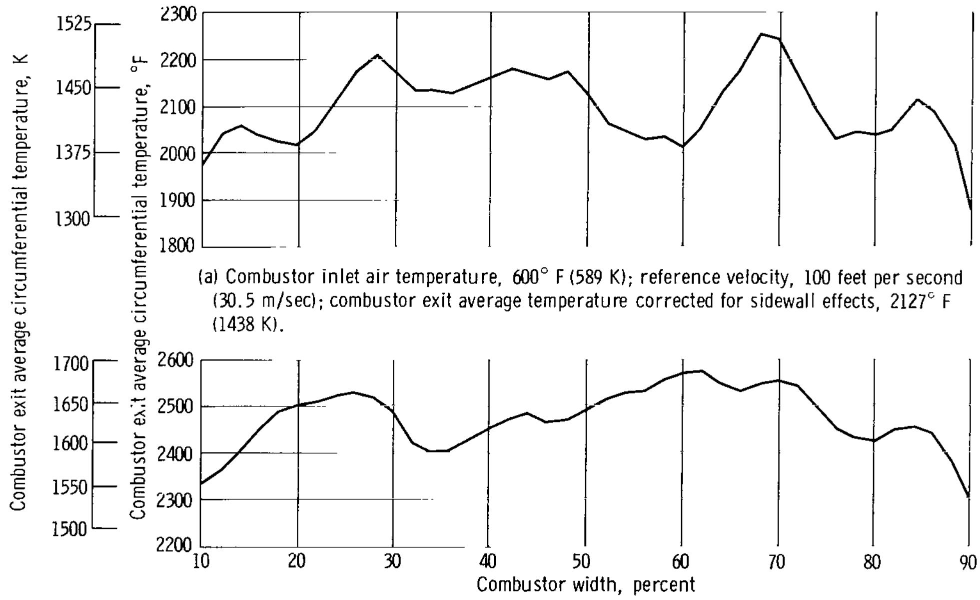
(b) View looking upstream.

Figure 4. - Combustor module array, model 3.



(c) Orientation of flame stabilizer plates.

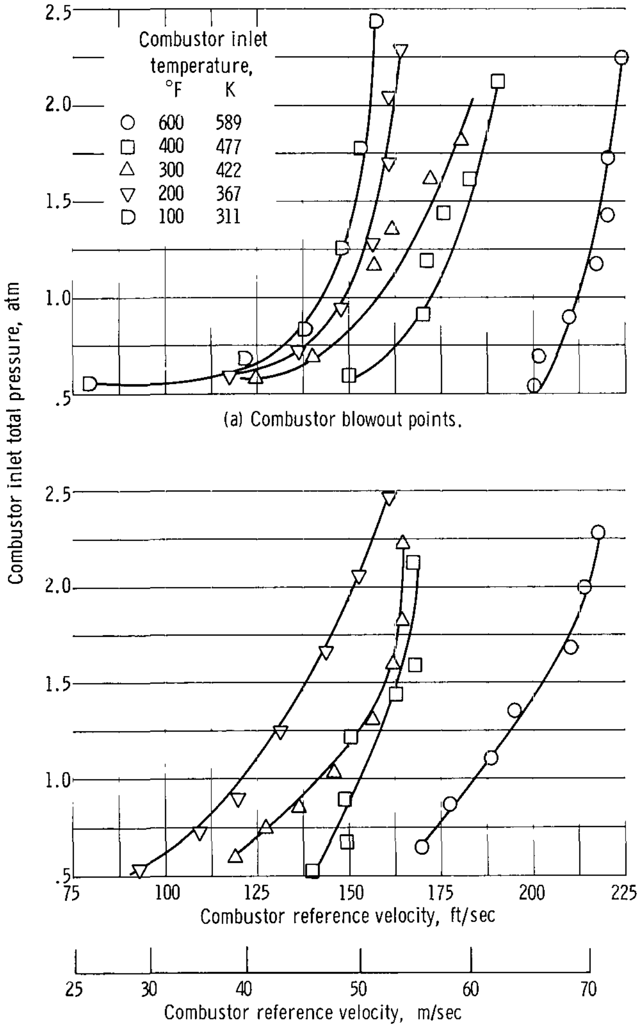
Figure 4. - Concluded.



(a) Combustor inlet air temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec); combustor exit average temperature corrected for sidewall effects, 2127° F (1438 K).

(b) Combustor inlet air temperature, 1150° F (894 K); reference velocity, 160 feet per second (48.8 m/sec); combustor exit average temperature corrected for sidewall effects, 2434° F (1605 K).

Figure 8. - Combustor exit average circumferential temperature profiles looking upstream for combustor model 2. Combustor inlet total pressure, 3 atmospheres.



(a) Combustor blowout points.

(b) Altitude relight points.

Figure 9. - Performance at altitude relight conditions. Fuel-air ratio, 0.017.

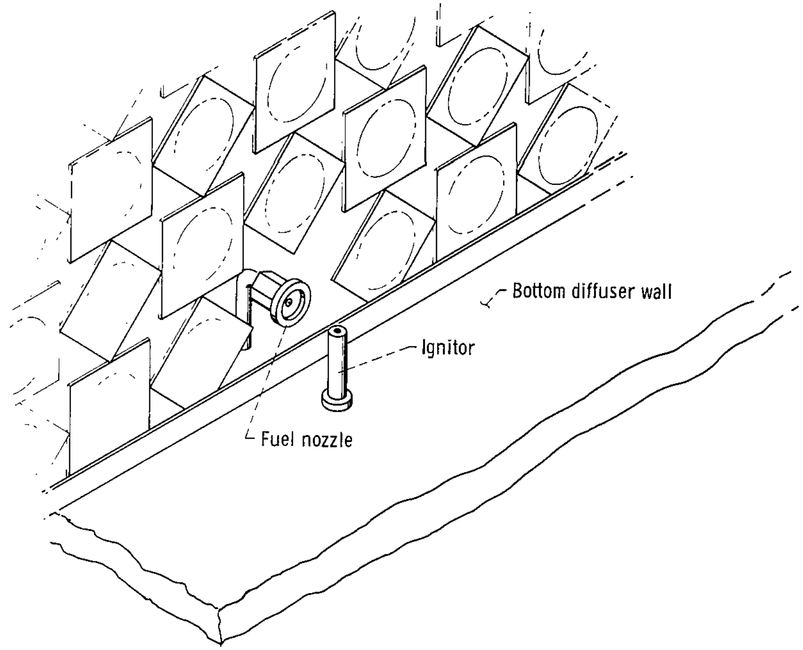
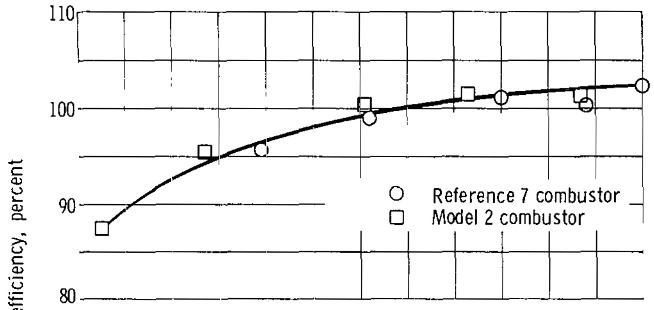
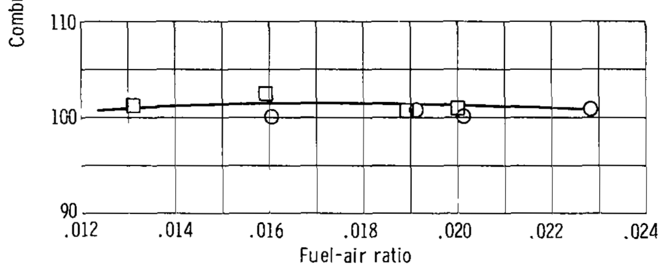


Figure 10. - Installation of fuel nozzle in combustor module array.



(a) Combustor inlet temperature, 600° F (589 K); nominal reference velocity, 100 feet per second (30.5 m/sec).



(b) Combustor inlet temperature, 1150° F (894 K); nominal reference velocity, 160 feet per second (48.8 m/sec).

Figure 11. - Comparison of combustion efficiencies for combustor model 2 and reference 7 combustor. Combustor inlet total pressure, 3 atmospheres.

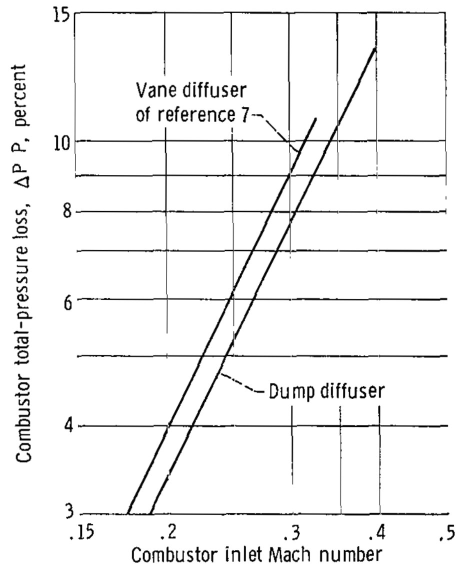


Figure 12. - Comparison of pressure losses for two diffuser configurations. Combustor inlet total pressure, 3 atmospheres; combustor inlet temperature, 600° F (589 K); combustor exit-to-inlet temperature ratio, 2.5.

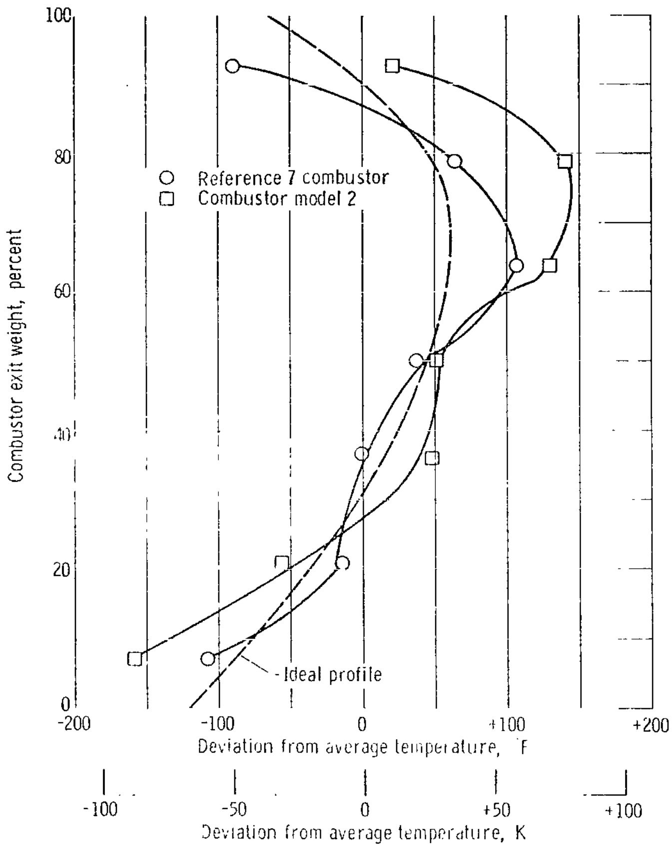


Figure 13. - Comparison of radial average combustor exit temperature profiles for combustor model 2 and reference 7 combustor. Inlet air pressure, 3 atmospheres; inlet air temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec).

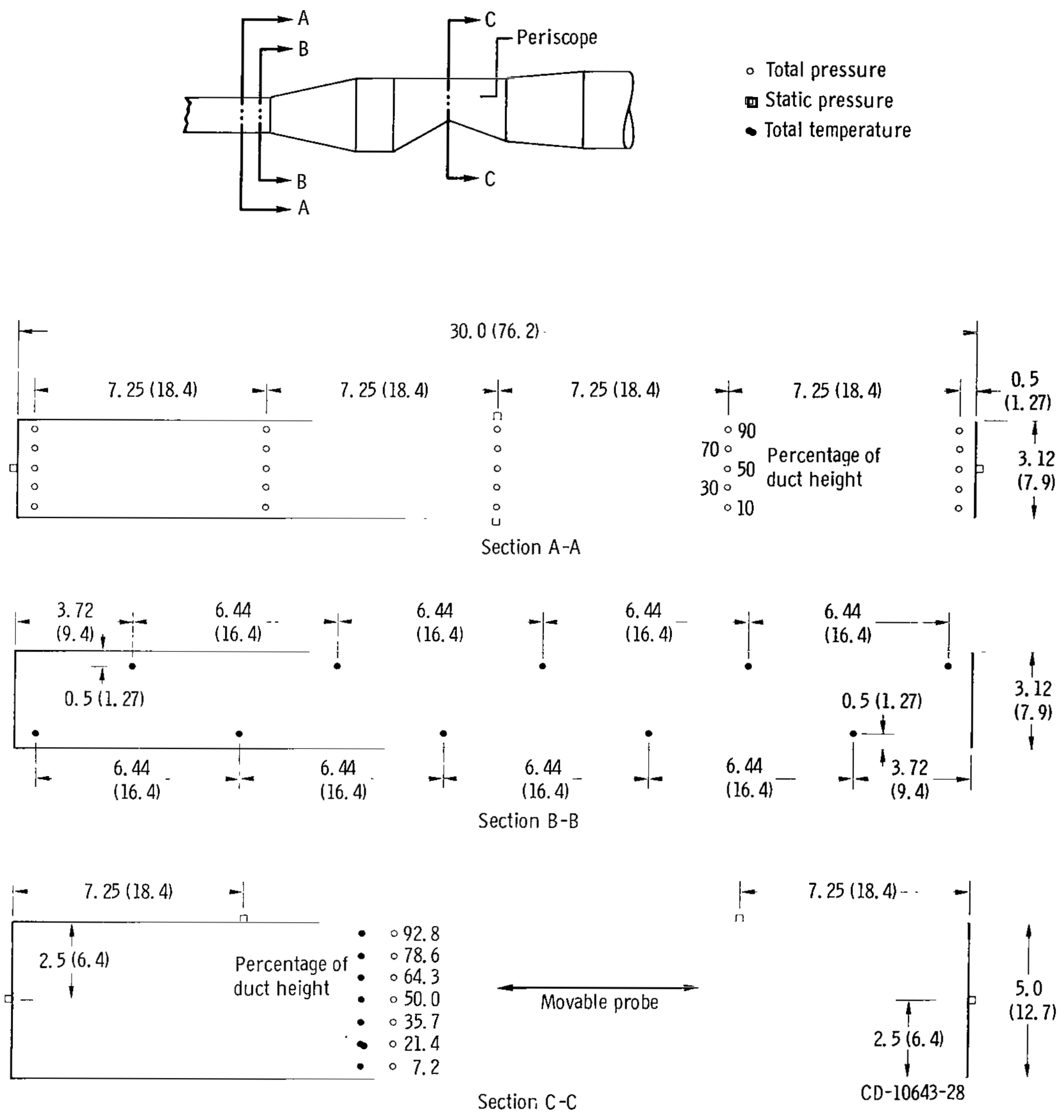


Figure 14. - Locations of pertinent instrumentation planes and locations of temperature and pressure probes in instrumentation planes. Dimensions are in inches (cm).

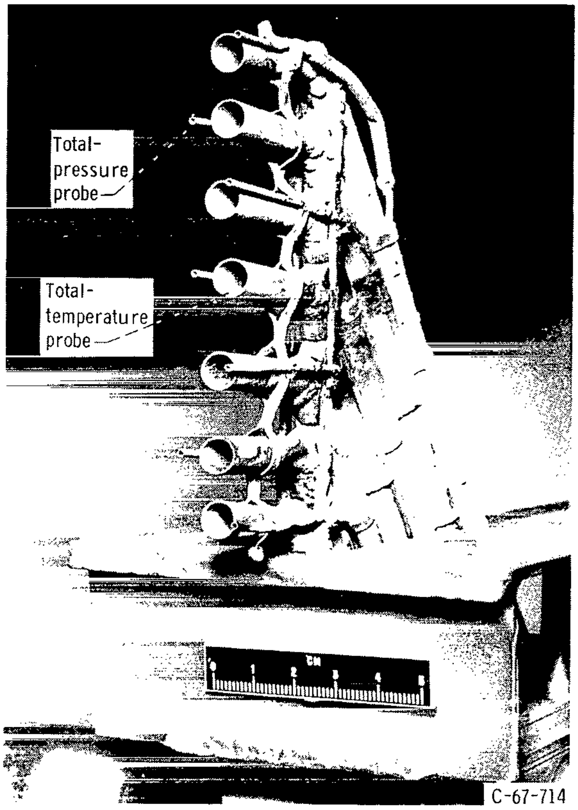
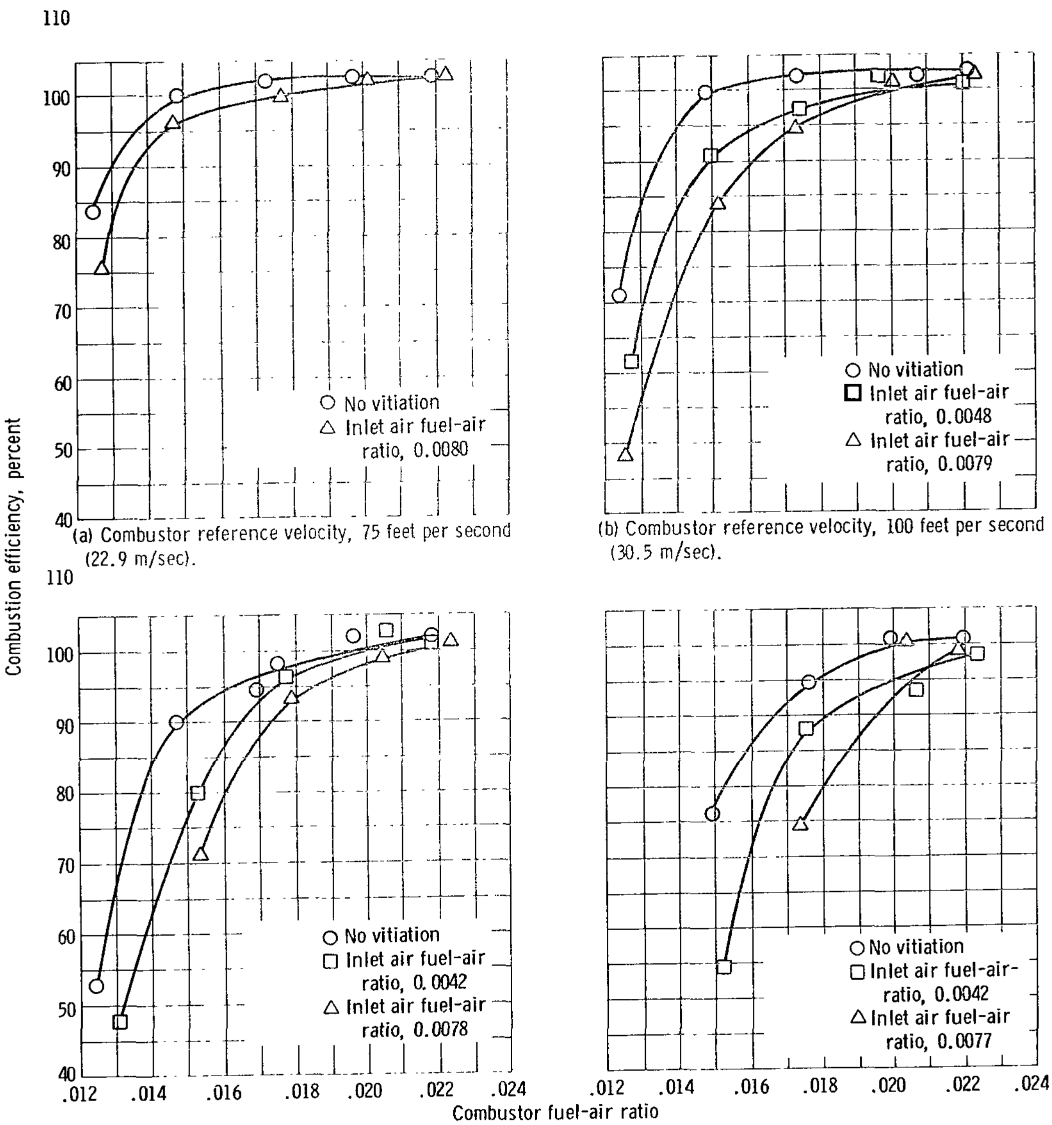


Figure 15. - Exit rake.



(c) Combustor reference velocity, 125 feet per second (38.1 m/sec).

(d) Combustor reference velocity, 150 feet per second (45.7 m/sec).

Figure 16. - Effect of vitiation on modular array combustion efficiency. Combustor inlet total pressure, 3 atmospheres; inlet air temperature, 600° F (589 K).

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